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FACTORS MODIFYING LUNG CANCER RISK IN ONTARIO URANIUM MINERS 1955–1981

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Résumé

On utilise la mortalité enregistrée chez les mineurs des mines d'uranium de l'Ontario jusqu'à la fin de 1981 pour analyser les effets de l'âge atteint, du temps écoulé depuis l'exposition et du tabagisme sur la probabilité du cancer du poumon à la suite de l'exposition aux descendants radioactifs de période courte du radon 222. On analyse également la relation qui pourrait exister entre l'exposition aux descendants du radon et le type de cellules cancéreuses.

Chez les mineurs des mines d'uranium de l'Ontario, le risque de cancer du poumon dû à une exposition aux descendants du radon est modifié par le temps écoulé depuis chaque incrément d'exposition. Le risque de cancer du poumon dû à un incrément d'exposition aux descendants du radon atteint un maximum entre 10 et 14 ans aprés l'exposition. Ce résultat modifie les projections faites pour évaluer le risque de cancer du poumon dû à l'exposition aux descendants du radon dans les mines et les habitations. Dans le cas des mines, le risque estimatif obtenu en utilisant le modèle du temps écoulé depuis l'exposition est inférieur d'un facteur 2, 3 à celui obtenu avec le modéle du retard de cinq ans. Dans le cas des habitations, le risque estimatif basé sur le modèle du temps écoulé depuis l'exposition est inférieur d'un facteur 3, 5. Le modèle du temps écoulé depuis l'exposition a également des conséquences du point de vue de l'identification des cancers du poumon provoqués par l'exposition aux descendants du radon.

On a constaté de plus que les données obtenues chez les mineurs des mines d'uranium de l'Ontario étaient compatibles avec un modèle multiplicatif du risque combiné de l'exposition aux descendants du radon et à la fumée de cigarette. Un modèle multiplicatif indique que le risque relatif de l'exposition aux descendants du radon est le même chez les fumeurs et chez les non-fumeurs. Il est important pour les projections de risque de l'exposition aux descendants du radon de déterminer comment le tabagisme et l'exposition aux descendants du radon se combinent dans le risque de cancer du poumon. C'est également utile quand on cherche à identifier les cancers du poumon qui sont dus à l'irradiation.

On a comparé la distribution des types cellulaires des cancers du poumon chez des mineurs des mines d'uranium de l'Ontario et chez des mineurs d'autres types de mines en Ontario. Compte tenu de l'âge moyen plus faible des mineurs des mines d'uranium atteints d'un cancer du poumon, on ne remarque aucune différence dans la distribution des types cellulaires pour les deux groupes de mineurs. Il est donc impossible d'utiliser le type cellulaire des cancers du poumon pour identifier ceux qui sont dus à l'exposition aux descendants du radon.

Summary

The mortality experience of Ontario uranium miners up to the end of 1981 is used to analyse the effects of attained age, time since exposure and smoking on the risk of developing lung cancer as a result of exposure to the short-lived progeny of ^{222}Rn (radon progeny). The association between exposure to radon progeny and the cell type of the lung cancer is also analysed.

In Ontario uranium miners, the risk of developing lung cancer from exposure to radon progeny is modified by the time elapsed since each increment in exposure was received. The lung cancer risk from an increment of exposure to radon progeny peaks 10 to 14 years after the increment in exposure was received. This finding modifies the projections of risk that are made to evaluate the lung cancer risk from exposure to radon progeny in mines and homes. For exposure in mines, the risk estimate obtained by using the time since exposure model is lower by a factor 2.3 than that obtained by using a five-year lag model. For exposure in homes, the risk estimate using the time since exposure model is lower by a factor of 3.5. The time since exposure model also has implications for the identification of lung cancer cases induced by exposure to radon progeny.

It was found also that the data from Ontario uranium miners are compatible with a multiplicative model for the combined risk from exposure to radon progeny and cigarette smoke. This indicates that the relative risk of exposure to radon progeny in smokers and non-smokers is the same. Determining how cigarette smoking and exposure to radon progeny combine to affect lung cancer risk is important in making projections of risk from exposure to radon progeny. It is also important when attempting to identify radiation-induced lung cancer cases.

The distribution of the cell types of the lung cancer cases in Ontario uranium miners was compared with that of lung cancer cases that occurred in non-uranium miners in Ontario. After taking into account the younger average age of the lung cancer cases among the uranium miners, no difference in the distribution of the cell types in the two groups of miners could be detected. The hypothesis that the cell type of the lung cancer could be used to identify those lung cancers that were induced by exposure to radon progeny is therefore not valid.

Introduction

Several epidemiological studies of miners have shown that exposure to high levels of radon progeny increases the risk of developing lung cancer (Lu71,Se73). It has been known for some time that lung cancer rates in Ontario uranium miners are greater than those of the Ontario male population (Mu73, Mu76), and it has been shown that exposure to radon progeny was the likely cause (Ha76), even though the levels of exposure to radon progeny in Ontario uranium mines were lower than in other uranium mines.

Many Ontario uranium miners have also worked in gold mines in Ontario. Underground miners in Ontario who were compensated for the development of silicosis are at increased risk of developing lung cancer (Fi82), and most of the miners who were compensated for the development of silicosis were employed in gold mines in Ontario. More recently, it has been shown that lung cancer and stomach cancer rates in Ontario gold miners are elevated compared to Ontario males (Mu83) and that the lung cancer rates were strongly related to the duration of employment in Ontario gold mines in the years before 1945 (Mu86,Ha87). Lung cancer risk is increased slightly in gold miners whose chest X-rays did not indicate signs of the development of silicosis and is increased by a larger amount in gold miners whose chest X-rays showed signs of the development of silicosis (Mu86). The study also indicated a weak association between lung cancer risk in gold miners and exposure to high levels of dust in ore bodies containing high levels of arsenic. The lung cancer risk in Ontario miners who mined neither gold nor uranium could not be shown to be increased (Mu83). The results of the study indicate that the increased risk of lung cancer in miners who had worked underground in the gold mines in Ontario before working in the uranium mines was partly due to employment in the gold mines and partly due to employment in the uranium mines, while the increased risk of lung cancer in the men who had worked in the uranium mines and mines other than gold was a result of employment in the uranium mines only (Mu84).

In an earlier report, two models of how exposure to radon progeny affected the risk of developing lung cancer were compared. One model is called the relative risk model, which says that exposure to radon progeny increases the lung cancer death rate in proportion to the product of the cumulative exposure to radon progeny and the lung cancer risk the miners would have if they were not exposed to radon progeny in the mines. The second model is called the absolute risk model, which says that the lung cancer death rate is increased in proportion to the cumulative exposure to radon progeny. The study showed that a relative risk model was affected less by attained age than the absolute risk model.

The study found that using the total exposure accumulated up to either five or 10 years before risk was evaluated did not significantly alter the fit of the relative risk model to the data (Mu84).

This report shows how smoking and time factors such as time since exposure and attained age affect the exposure response function in Ontario uranium miners. It also reports on the relationship between exposure to radon progeny and the cell type of the lung cancer.

Sources of data

Since 1928 the Ontario *Mining Act* has required that provincial government agencies carry out pre-employment examinations and yearly chest X-ray examinations for all employed miners in Ontario and for men entering the mining industry in Ontario. At these

examinations, the miner provides a history of his mining employment up to the time of the examination. This information is forwarded to the Ontario Workers' Compensation Board. In 1955 the work histories for those miners who had worked in dusty occupations for at least 60 months were transferred to computer cards and later onto computer tape. As part of this study, these work histories were expanded to include miners who had worked at least two weeks in an Ontario uranium mine.

The Canadian Mortality Data Base (MDB) for the years 1955 to 1981 was searched at Statistics Canada to locate the death certificates of Ontario uranium miners. The searching was done using the probabilistic file linkage methods developed at Statistics Canada. Before searching the MDB, the Social Insurance Number Registry was used by Statistics Canada to obtain data items such as mother's maiden name for each miner whose Social Insurance Number was recorded on the WCB's data file. These additional data items increased the power of the file linkage procedure. The likelihood of the correctness of each linkage between an Ontario uranium miner and a death certificate was determined by comparing the data elements that were on both the death certificate and the work history but were not available on the computerized record used for the file linkage. Items such as prior knowledge of death, good agreement on the nature of employment and, in some time periods, the month and day of birth were used to accept links.

The file linkage procedures were used at Statistics Canada also to link the list of Ontario uranium miners and the list of employees of Eldorado Nuclear Limited, which operated uranium mines in the Northwest Territories and Saskatchewan and a refinery in Port Hope, Ontario. Ontario uranium miners who were found on the list of employees of Eldorado were excluded from the study, as were men who were known to have been exposed to asbestos in the workplace.

The level of short-lived radon progeny in air is measured in units called Working Levels (WL). A Working Level of short-lived radon progeny means that the potential alpha energy of the short-lived radon progeny in one litre of air is 1.3×10^8 million electron volts. Measurements of the levels of radon progeny in Ontario uranium mines were begun in 1958 using the Kusnetz method (Ku56). Measurements of the levels of radon progeny were made by the mine operators, who reported the results of their surveys to the appropriate government agencies every three or four months. Provincial agencies calibrated the instruments used by the mining companies. These reports contained the average, minimum and maximum levels determined in three-month or four-month periods in headings, stopes, raises and travelways. The estimates of exposure were calculated by a time-weighted average of the concentration of radon progeny in work areas (stopes, headings and raises) and travelways. The relative time-weights were 80 per cent for work areas and 20 per cent for travelways. The 'standard' estimates of the average level of radon progeny in each mine during each calendar year are averages of the three-month or four-month averages given in these reports, and the 'special'

estimates of exposure are time-weighted averages of the maximum values contained in these reports. In this report, only the 'standard' WL values are used to estimate exposure to radon progeny as these values are considered more reliable than those made on the basis of the 'special' WL estimates.

The level of radon progeny had to be estimated in all mines that started operation before 1958, and the values reported up to the end of 1960 in one mine were also estimated because the mine's measurements were considered unreliable. The extrapolation procedure was developed by a group of mining engineers who were familiar with uranium mines in Ontario. The procedure used tonnage produced, ventilation parameters and the results of dust counts to estimate the annual average level of radon progeny in each operating mine when measurements were not available.

The unit of measurement of exposure to radon progeny is called a Working Level Month (WLM), which is the product of the level of radon progeny in the mine's air and the duration of time spent exposed to that level of radon progeny. One working month is considered to be 170 hours. Each uranium miner's exposure in each calendar year up to the end of 1967, and up to the end of March 1968 in one mine, was estimated by multiplying the average concentration of radon progeny in the mine during the year the miner worked there by the number of months the miner worked in the mine in that year. This estimate of the miner's exposure to radon progeny was adjusted by taking into account the effect of overtime, work stoppages, strikes and holidays in the mine during the year. This estimate was further adjusted for the time spent working underground; employees such as electricians and maintenance workers were assumed to spend 50 per cent of their time underground when their exposure to the radon progeny was calculated. This general approach to estimating the exposure to radon progeny has been used in other studies of mining populations (Lu71,Se73,Ha76).

Starting in 1968, each miner's exposure to radon progeny was reported by his employer to the Atomic Energy Control Board. These individual exposure estimates were based on the miner's daily reports of the time he spent in each workplace and recent measurements of the level of the radon progeny in those workplaces.

The accuracy of the work history data was investigated. Officials of the Atomic Energy Control Board (AECB) in Elliot Lake examined the mining companies' employment records for 50 uranium miners who had been chosen at random for tracing as part of the study of the smoking habits of Ontario uranium miners. The company employment records and the estimate of the mine average concentration of radon progeny used in this study were used by the officials of the AECB to estimate the exposure to the radon progeny.

AECB officials in Elliot Lake provided data about the number of times that measurements of the radon progeny concentrations were made in each mine during each year of operation.

Smoking histories of Ontario uranium miners who had died of lung cancer were collected from hospital records, the physician who had treated the miner, next-of-kin or other miners. Information was sought on whether the miner ever smoked cigarettes, how many cigarettes he regularly smoked, his age when he started to smoke cigarettes regularly and the year when he quit smoking.

A random sample of all uranium miners born before 1939 formed the control group for the case-control study of the joint effect of smoking and exposure to radon progeny. After excluding miners who either worked in an asbestos mine or at Eldorado, there were 226 non-gold uranium miners in the control group. Smoking histories, containing the data described above, were sought from the miner himself, if he could be found, or, from his next-of-kin, other miners and the files of the chest clinic operated by the Occupational Health and Safety Division of the Ministry of Labour.

Tissue blocks or slides from uranium miners and non-uranium miners who had developed lung cancer were collected from hospitals where biopsies or post mortem examinations were done. In most instances, lung tissue was examined, although in some instances lung cancer cells had metastasized to the lymph nodes were examined. When a tissue block or slide could be obtained, one of the authors (A.C.R.) re-evaluated the classification of the cell type using the World Health Organization classification of lung cancers (WHO82).

Methods

A retrospective mortality study of the risk of various causes of death, with emphasis on lung cancer mortality resulting from exposure to radon progeny in Ontario uranium mines, was done. A nested case-control study was used to investigate how smoking modified the risk from exposure to radon progeny.

The population of Ontario uranium miners was divided into three groups according to the type of exposure: miners who had ever worked in a uranium mill in Ontario are called mill workers; uranium miners who were not mill workers and who had been employed in an Ontario gold mine before working in an Ontario uranium mine are called gold-uranium miners; and underground uranium miners who were not mill workers and who had not been employed in an Ontario gold mine before working in an Ontario uranium mine are called non-gold uranium miners. Uranium miners who had no recorded exposure to the radon progeny and who had not worked on the surface and men who first worked in an Ontario uranium mine after January 1, 1978 were not included in the analysis.

The person-years at risk of dying for each uranium miner were counted from the earliest time when employment in Ontario uranium mines was known to exceed one-half month

up to the time of death or December 31, 1981. In some instances employment in the uranium mines was known to exceed one-half month because of a report from a uranium mining company and, in other cases, because of a report made to the chest clinic by the miner. In the latter instance, person-years at risk of dying were counted from the time when the report was made rather than from the time when employment in the uranium mine began. The period of observation for mortality ended on December 31, 1981 and only deaths found by Statistics Canada were used in the analysis.

The expected number of deaths for various causes were calculated using the age and calendar specific death rates for Ontario males.

The observed number of deaths was assumed to be an observation from a Poisson distribution and the mean of the Poisson distribution was the expected number of deaths. The hypotheses being tested were that the death rates due to particular causes were not increased and one-sided P-values smaller than 0.05 are reported. The causes of death that were of interest were lung cancer, stomach cancer, leukemia, silicotuberculosis, silicosis and accidental deaths.

When the exposure response functions were evaluated, risk was measured as either 'Attributable Risk' or 'Excess Relative Risk'. Both measures of risk include the excess number of cases, which is defined as the difference between the observed and expected numbers of cases. Attributable risk is defined as the ratio of excess number of cases to person-years at risk of dying, and excess relative risk is defined as the ratio of the excess number of cases to the expected number of cases.

Exposure to radon progeny was modelled in two ways. In the first model, called Model I, risk was related to exposure to radon progeny accumulated prior to an interval of time called the lag period. According to this model, exposure accumulated during the lag period does not increase lung cancer risk. Lag periods of 5, 10 and 15 years were used. For each miner, lagged exposure to radon progeny was evaluated for each year he was at risk of dying. Seven exposure intervals were formed in order to group the data. For each year that a miner was at risk of dying, person-years at risk of dying and expected numbers of deaths were accumulated in the exposure group to which he belonged in that year. When a miner died of lung cancer, his death was added to the observed number of deaths in the exposure group determined by his lagged total exposure evaluated in the year of death.

The second method of measuring exposure, called Model II, took into account the elapsed time since each annual increment in exposure to radon progeny. At each year when risk and exposure to radon progeny were evaluated, the past exposures were totalled according to the time elapsed since the exposure was received. For the purpose of fitting the model to the data, the time intervals five to nine years, 10 to 14 years and 15 or more years were used. These time windows were chosen to be five years wide as the use of

more time windows of shorter length would result in unreliable estimates of risk and exposure in each time window, and the 15 years or more category was the last category as, even at the end of 1981, there were few miners at risk from radon progeny exposure 20 or more years earlier. For each year-at-risk of dying, each miner's radon progeny exposure was accumulated in each time window and each accumulation was placed into one of three exposure groups: 0 WLM, 0.1 to 29.9 WLM, and 30 WLM or greater. In addition, the observed and expected numbers of lung cancer deaths and the person-years at risk of dying in each time window and exposure group were classified by three attained age groups: under 45 years, 45 to 54 years and 55 years or over. The risk functions were fit to the data by using a regression technique known as iterative re-weighted least-squares, or Poisson regression (Fr83).

The case-control data were analysed using a standard technique for matched pairs (Br80).

The smoking habits of the uranium miners were classified as either 'smoking regularly 10 or more cigarettes per day at any time in the 10 years prior to the evaluation of risk' or 'smoking regularly fewer than 10 cigarettes per day prior to the evaluation of risk'. Cases and controls were matched for age and total exposure to radon progeny accumulated when they were 10 to 14 years younger.

The comparison of the distribution of cell types in uranium and non-uranium miners was done using Fisher's exact test, and one-sided P-values are reported.

The lifetable for Ontario males for the years 1975 to 1977 and lung cancer rates observed in Ontario males in the years 1974 to 1978 were used in the projection of risk from various exposures to radon progeny based on excess relative risk models. When Model II was used in the risk projection, the risk coefficients from the five to nine year time window and the 10- to 14-year time window were used. The risk from continual exposure to radon progeny at the rate of 1 WLM per year was evaluated using Model I and Model II. The risks resulting from continual exposure from birth and from age 20 to age 75 were evaluated. The risk from short exposures at various ages was also investigated using both the models. The effect of higher or lower rates of exposure to radon progeny can be estimated by scaling up or down the results shown in this report.

Results

There were 10,661 non-gold uranium miners and 4,216 gold uranium miners. Tables 1 and 2 show mortality for the three groups of uranium workers.

In both gold-uranium and non-gold uranium miners, more deaths were observed than expected. The increased risk of dying was mainly due to an increased risk of death due to violent causes. In both groups of uranium miners, the risks of death due to lung cancer, silicosis and chronic interstitial pneumonia were increased. In gold-uranium miners, the risk of death due to stomach cancer was also increased.

The death rate from malignancies of the lymphatic and haematopoietic tissue was not increased in any of the sub-cohorts of uranium miners. No increased death rate was observed from any specific cause of death included in this group of causes. In uranium miners who never worked in the mill, there were no observed deaths due to non-acute lymphatic leukemia compared to 2.1 expected; four observed deaths due to non-acute myeloid leukemia compared to 2.3 expected; two deaths due to multiple myeloma compared to 4.1 expected; 17 deaths observed due to other lymphatic cancers compared to 18.2 expected; and nine deaths observed due to other leukemia compared to 8.6 expected.

The number of deaths in mill workers did not exceed the expected number of deaths, and there is no evidence of an increased risk of death for any of the causes shown in Table 2.

Figure 1 shows the number of measurements of radon progeny made in each calendar year since 1954 and the total exposure received by uranium miners in each year. Although 23 per cent of the total exposure received up to the end of 1977 was estimated, the maximum time span over which the extrapolation was made was 4.5 years, and 84 per cent of the extrapolated exposure was received within two years of the time when measurements of the concentration of radon progeny were made.

Figure 2 shows the comparison of the radon progeny exposure estimates derived from company employment records and the records obtained from the chest examination station. Two miners were excluded from the comparison because they were found to be mill workers. Using ordinary least squares regression, the slope of the function was calculated to be 0.96 and the intercept was calculated to be 6.7 WLM. The square of the correlation coefficient was calculated to be 0.96. The regression analysis indicates that the work history obtained from each miner at the miners' examination agreed well with the employment data in the company files.

Figure 3 shows the distribution of the years of birth in both groups of uranium miners. The non-gold uranium miners were younger than the gold-uranium miners.

Table 3 shows the data used to fit Model I to the data when the standard Working Level estimates were used to evaluate exposure.

Table 4 shows the results of fitting the absolute risk and the excess relative risk to cumulative exposures lagged by five, 10 or 15 years. The analysis shows that the risk functions for non-gold uranium miners and gold uranium miners are different. The intercept of the excess relative risk function for gold uranium miners is different from zero ($P<0.05$) while for non-gold uranium miners the intercept of the excess relative risk function is close to zero when the exposure is lagged by either five or 10 years. The slope of the excess relative risk function for non-gold uranium miners is 1.3 per cent per WLM for both the five-and 10-year lag period and is different from zero ($P<0.001$). In neither gold uranium miners nor non-gold uranium miners could there be demonstrated a significant association between excess relative risk and exposure to radon progeny accumulated 15 or more years prior to the evaluation of risk.

The results for the attributable risk function are somewhat different. The intercept for the gold uranium miners is different from zero ($P<0.01$) and cannot be shown to be different from zero for non-gold uranium miners. In non-gold uranium miners, the association between attributable risk and exposure is stronger when exposure is lagged by five or 10 years than when it is lagged by 15 years. The attributable risk function for gold uranium miners shows a strong association between risk and exposure to radon progeny regardless of the lag period.

Table 5 shows the data used to fit Model II to the data. Each row in the table represents a different combination of age group and exposure level in each of the three time windows. When using the time window approach, the total number of possible categories into which the data could fall is 81: three age groups multiplied by the number of exposure groups in each time window raised to the power 3, which is the number of time windows used (3×3^3). There were 76 data points, which is five fewer than could have occurred.

Table 6 shows how the time window approach affects the exposure risk relationship. The deviance is a measure of the lack of fit between the data and the model. The improvement in the fit of a series of models obtained by adding new variables to the previous model can be measured by considering the difference in the deviances of successive models to be a chi-square statistic with degrees of freedom being the difference in the degrees of freedom of the models.

Because equation 1 can be re-written as:

$$(O-E)/E = -0.12 + 0.015 \times (WLM_{5-9} + WLM_{10-14} + WLM_{15+}),$$

equations 1 and 2 can be compared to test the hypothesis that time since exposure does not affect excess relative risk. The hypothesis cannot be accepted ($P=0.02$). The comparison of equations 2 and 3 is used to test the hypothesis that attained age does not further affect the excess relative risk function. The hypothesis cannot be rejected ($P=0.6$). The comparison of equations 1 and 4 can be used to test the composite hypothesis that the risk coefficients for the radon progeny exposure accumulated in the five- to 9-year

time since exposure window and the 15 years or more time since exposure window are both zero. The hypothesis cannot be rejected (P=0.4). In summary, the analysis shows that when using the excess relative risk model, the time since exposure effect results in a better model than the five year lag model, that including attained age does not appear to result in further improvements and that most of the radiation-induced risk from an increment in exposure occurs 10 to 14 years after the increment in exposure was received. A similar set of comparisons for the attributable risk model shows that the time since exposure effect is not apparent in this type of risk model.

Smoking data were collected for 91 per cent (73/80) of the lung cancer cases and 61 per cent (140/226) of the controls in the non-gold uranium miner population. The duration of employment and the total exposure to radon progeny of controls for whom smoking histories were found was higher than for controls for whom smoking histories were not found. If these differences were ignored, they would introduce a bias in any analysis of the effect of radon progeny exposure on lung cancer risk. In order to control this bias, the amount of exposure to radon progeny 10 to 14 years prior to the evaluation of risk was used also to match cases with controls. There were 69 matched pairs because controls for three lung cancer cases could not be found.

The matched pairs were divided into two groups according to whether the pair had any occupational exposure to radon progeny when they were 10 to 14 years younger. Based on the analysis of the mortality and exposure data for all non-gold uranium miners, the group of men with no exposure to radon progeny 10 to 14 years earlier are at low risk of developing lung cancer from exposure to radon progeny and the other group is at high risk of developing lung cancer from the exposure to radon progeny. Table 7 shows that the relative risk due to smoking is 14 to 1 in those pairs who are at high risk from exposure to radon progeny and 17 to 0 in those at low risk from exposure to radon progeny. There is no statistical difference in the two relative risks.

Table 8 shows the results of the histological re-evaluation of the lung cancer cases. Forty seven per cent (167/354) of the lung cancer cases in non-uranium miners and 59 per cent of the lung cancer cases in uranium miners were re-evaluated. There is a greater proportion of small cell cancers in uranium miners than in non-uranium miners (50 per cent vs 34 per cent, P = 0.009). However, the lung cancer cases who were uranium miners were younger than the lung cancer cases who were not uranium miners. The proportion of lung cancer cases who were re-examined and who were under the age of 60 was 72 per cent for uranium miners and 37 per cent in non-uranium miners. The strength of the association between the increased risk of developing a small cell lung cancer and uranium mining is decreased when age at death is taken into account. Under the age of 60, there is no detectable difference in the proportions of small cell lung cancers in uranium and non-uranium miners (P = 0.1). Over the age of 60, there is also

no detectable difference in the proportions of small cell lung cancers in uranium miners compared to non-uranium miners (P = 0.2).

Figure 4 shows the number of lung cancer deaths would occur in a cohort of 100,000 new-born males who were followed up to the age of 75. Model I predicts that there would be 3,976 extra lung cancer deaths if exposure to 1 WLM per year began at birth and 2,653 extra lung cancer deaths if exposure began at age 20. Model II predicts that there would be 1,143 extra lung cancer deaths exposure began at birth and 1,142 if exposure began at age 20.

Figure 5 shows how Model I predicts the age distribution of extra lung cancer deaths that would occur up to the age of 75 if exposure to 1 WLM per year lasted for five years and began at various ages.

Figure 6 shows how age at first exposure affects the extra number of lung cancer deaths up to the age of 75 predicted by Models I and II when the exposure rate is 1 WLM per year and the duration of exposure is five years.

Discussion

Ontario non-gold uranium miners are a relatively young population. By the end of 1981, 44 per cent of these miners were 46 years old or younger. Up to the end of 1981, only 978 deaths, 9 per cent of the cohort, were observed in 10,661 non-gold uranium miners. Lung cancers are quite rare at these ages; only 2 per cent of the lung cancers that occurred in males in Ontario in 1981 were in men under the age of 45. The young age of the non-gold uranium miners is a substantial limitation of the study, and a much longer period of observation is required to confirm and refine conclusions drawn from the data observed up to the end of 1981.

Mortality from various causes are given separately for non-gold uranium miners, gold uranium miners and mill workers. Some members of the latter group had also worked for some time underground, and their total exposure to alpha emitters both underground and in the mill could not be assessed. They were therefore excluded from calculations relating to underground uranium miners.

The results show that the death rates in gold uranium miners are significantly higher than in Ontario males. The death rates from malignant neoplasms are increased, largely due to an increased death rate from cancer of the trachea, bronchus and lung. The death rate from cancer of the stomach is also significantly increased in the same group of miners. Non-gold uranium miners show no significant increase in stomach cancer rates, and gold uranium miners have an increased risk of dying of cancer of the stomach (SMR = 203, P = 0.004). It should be noted that an increased risk of stomach cancer was also observed in gold miners who started gold mining *after* 1945 (Mu86).

Significantly increased death rates from silicosis and chronic interstitial pneumonia, as well as from accidents, poisoning and violence, were observed in both underground miner cohorts. In this respect, the results in these cohorts do not differ from those obtained in gold miners (Mu86) and 'mixed ore' miners (Mu87).

Men who ever worked in a uranium mill showed no significant increase in death rates for any group of causes. The number of expected and observed deaths is, however, small.

The calculated coefficients of the Model I risk functions given in this report do not differ in any substantial way from those given in the 1984 report. There are, however, some minor numerical differences. The number of observed and expected lung cancer cases was affected by the more rigorous exclusion of underground uranium miners with some exposure in uranium mills. Also, exposure is evaluated somewhat differently; it is now accumulated to the beginning rather than to the end of the year in which risk is being evaluated. If exposure is lagged by five years, for example, exposure is accumulated only up to the beginning of the fifth year preceding the time of observation, rather than to the end of the fifth year preceding the time of observation, as was done in the earlier study (Mu81). As can be seen, however, these changes did not affect the results in any significant way.

The effects of age, time since exposure and smoking on lung cancer risk have been considered in various studies. Lundin and co-workers (Lu71) tested dynamic exposure-time-response models using the exposure and mortality data of uranium miners on the Colorado plateau. Their model assumes that the time distribution of lung cancer risk following exposure to radon progeny has approximately the same shape and dispersion, but not necessarily the same mean, as leukemia incidence following single exposure to ionizing radiation (Do66). In their model, a lognormal distribution of risk with time following exposure was used. They assumed that the exposure-response function was linear, and thereby independent of the dose rate, and that the geometric standard deviation of the lognormal time response function was 1.5. The authors found that absolute risk models with a median time interval between exposure and response of five, 10 and 15 years did not fit well to the data. They tested a relative risk model and found that a median time lag of 10 years between exposure and response fit the data best. They also found that the general shape and the median latency of the time response function is independent of the magnitude of the exposure. Their best fitting exposure-time-response model indicates that 68 per cent of the risk from an increment in exposure to radon progeny occurs between 6.7 and 15 years following that exposure.

Sevc and Placek (Se73) observed a decline in lung cancer risk after more than 18 years following the start of underground mining. No data are given on risk per unit exposure at the various time intervals since the start of mining. It appears, nevertheless, that the Czechoslovakian data indicate a decline in relative lung cancer risk more than 18 years following the onset of exposure to radon progeny in the mines.

Harley and Pasternack (Ha81,NCRP84) proposed two models for describing the effect of time since exposure on risk per unit exposure to radon progeny. Model A assumes that the attributable risk from unit exposure commences at age 40 after a latency of a minimum of five years and remains constant thereafter. Model B also assumes a latency of five years and no radiation-induced tumours to manifest themselves before age 40. The uniform rate of appearance in time after age 40 assumed in Model A is, however, corrected in Model B by an exponential function with a half-life of 20 years. The exponential term of Model B corrects for removal of transformed cells with time through cell repair or cell death.

Hornung and Meinhardt (Ho86) investigated the effect of time since cessation of occupational exposure to radon progeny. They found that the relative risk of radiation-induced lung cancer diminishes with time after cessation of exposure.

The time of cessation of exposure is a rather arbitrary point in the exposure history of a uranium miner. Exposure rates in the mines have been declining over the years and the time lag between individual exposure increments and the end of the study or death varies greatly in long term chronic exposure. In addition, cessation of exposure might, in some instances, be associated with illness, which might lead to death within a few months or years following cessation of exposure. If the intention is to measure the effect of time since exposure on risk, a different approach might have to be used.

In this report a dynamic model, relating radiation-induced lung cancer risk to time since individual yearly increments of exposure, is presented and applied to the data observed in Ontario uranium miners. Model II is similar to that proposed by Lundin and co-workers (Lu71). No assumption has, however, been made in Model II about the shape of the time-response function. Taking into consideration both exposure rates and total exposure of Ontario uranium mines, it was assumed that the exposure-response function in each individual time window was linear.

Because the fitting of this model to the data requires the use of a multivariate statistical technique, the data are categorized into many small groups. There are 76 different categories into which the data can be placed and, with a total of 80 lung cancer cases, there is an average of one lung cancer case per category. When the data are divided into so many small subgroups, there is concern about whether reliable results can be obtained from the quality of data that were used in this study. The results from Model I and Model II can be compared to evaluate the reliability of the new approach. The regression coefficients calculated when exposure is lagged by five years using the seven exposure groups shown in Table 4 and the 76 categories shown in Table 6 are comparable. The slopes of the equations are 1.3 per cent per WLM and 1.5 per cent per WLM and the intercepts are -0.05 and -0.12. It is also interesting to note that both Models I and II show a weak association between excess relative risk and radon progeny exposure received 15 or more years before the evaluation of risk.

Table 6 indicates that exposure accumulated in the time window 10 to 14 years ago contributes most to excess relative risk. The excess relative risk of exposure received 15 or more years ago is 0.3 per cent per WLM. Although this is small compared to the risk coefficients in the other intervals of time since exposure, ignoring the risk from exposure received 15 or more years ago greatly affects the projection of lifetime risk from exposure to radon progeny.

Projection of the risk from environmental exposures must take into account the risk from exposure at very young ages. At present, there is no quantitative information on lung cancer risk from exposure to radon progeny in childhood. Risk functions derived from the Ontario non-gold uranium miners were, however, applied to the male population at large to calculate the risk of dying of radiation-induced lung cancer up to age 75 years.

If exposure to 1 WLM of radon progeny per year begins at birth, Model I predicts the extra risk of dying of lung cancer up to the age of 75 years is about 3.5 times greater than that predicted by Model II. If exposure to 1 WLM per year starts at age 20 years, Model I still gives a risk about 2.3 times greater than Model II. Model II, if applicable to childhood exposure to radon progeny, indicates that the extra lung cancer risk is no different for those starting exposure to a constant rate at birth than it is for those starting at age 20 years. If these risk projections for childhood exposures are valid, they indicate that there is considerable repair or elimination of cells induced prior to age 20.

Although the applicability of this model to childhood exposure cannot be tested on groups of uranium miners, it would be most desirable to test this model on mining populations who have been exposed early in life. Ontario uranium miners are a young cohort and most of them have worked for short periods underground. For both these reasons, Ontario uranium miners are a suitable group for studying the effect of time since exposure on lung cancer risk.

The predicted number of radiation-induced lung cancer deaths resulting from short-term exposure is greatly dependent on the age at which exposure occurs. As the age of first exposure increases, Model I predicts fewer radiation-induced lung cancer deaths resulting from short-term exposure. In comparison, Model II predicts that short-term exposure early in life results in fewer radiation-induced deaths than the same exposure later in life. This is demonstrated in Figure 6. If short-term exposure started early in life, the number of radiation-induced lung cancer deaths up to the age of 75 years predicted by Model II is relatively small compared to the number predicted by Model I. If exposure started later in life, the two models give more comparable results and, under certain conditions of exposure, Model II predicts a higher risk per unit exposure than Model I.

Uranium miner cohorts are composed of cigarette smokers and non-smokers. Smokers include present and past smokers, heavy smokers and light smokers. They might inhale tobacco smoke to various degrees and they might smoke cigarettes with or without filter

tips. All these factors might affect lung cancer risk resulting from the exposure to radon progeny.

There are at present few studies on non-smoking cohorts of uranium miners. One study of a cohort of Navajo Indians clearly indicates a significantly increased lung cancer risk in non-smoking uranium miners (Sa84).

Several authors have investigated the lung cancer risk resulting from the interaction of cigarette smoke and exposure to radon progeny. There is, however, still no consensus on how they interact. Some studies suggest that the lung cancer risks resulting from the inhalation of cigarette smoke and radon progeny are additive (Ed82, Ra84). Other studies (Ar73, Wh83, Da85) suggest that the two types of exposure act in a multiplicative way. One study indicates that cigarette smoke diminishes the risk per unit exposure to radon progeny and thus exerts a protective action (Ax78). The possible reasons for these discrepancies have been discussed (Da85).

The Ontario uranium miners' mortality study indicates that the relative lung cancer risk due to smoking is not dependent on exposure to radon progeny. This finding is compatible with the hypothesis that inhaled cigarette smoke and radon progeny interact multiplicatively. However, the number of lung cancer cases who smoked fewer than 10 cigarettes per day is small.

A variety of occupational exposures has been linked to small cell carcinomas. The excess of lung cancer reported among chloromethyl methyl ether workers was almost entirely attributable to small cell carcinoma (Fi73). Exposure to radon progeny is known to increase lung cancer risk and this increase in risk is considered by some authors (Ho77) to be mainly due to the increase in frequency of squamous cell and small cell cancer. Earlier, Archer and co-workers (Ar74) reported an increase in squamous, small cell and undifferentiated lung cancers and also in adenocarcinomas in uranium miners. The number of adenocarcinomas was, however, small. The rate of cancer of the various cell types increased with exposure. The greatest increase was, however, in small cell cancer.

Cigarette smoking might affect the distribution of lung cancers by cell type. Some authors (We72) found a positive association of cigarette smoking with well-differentiated squamous cell carcinoma, small cell carcinoma and adenocarcinoma. Also, Lubin and co-workers (Lu81) found, in a large hospital-based case-control study, that the relative risk increased with duration of cigarette use for all histologic types. The gradient of risk was, however, greater for squamous cell cancer than for adenocarcinoma. Also, the risk of squamous cell cancer declined more sharply after cessation of smoking than the risk of adenocarcinoma. Other authors (Au75) found that the frequency of small cell carcinomas increased with cigarette consumption in men under the age of 70 years, but the frequency of epidermoid cell cancer or adenocarcinoma did not.

Attained age is another parameter that might affect the distribution of the cell types of cancer. Data derived from a study of coal miners (Va85) show that the fraction of small

cell cancers decreases and the fraction of squamous cell cancers increases with age of the cancer patient. Others have noticed that undifferentiated cancers (large cells, oat cells and round cells) are found more often in younger age groups than in other types (Ti77). As the number of years smoked and also the number of pack-years smoked are associated with attained age, the effects of age and years smoked cannot easily be separated.

Table 8 shows that uranium miners have a significantly higher fraction of small cell cancers than non-uranium miners. This is, however, largely due to the fact that uranium miners are younger than non-uranium miners (Mu83). For the same reason, the age at death from lung cancer is also lower in uranium miners than in non-uranium miners.

Conclusions

(1) Underground uranium miners, with and without previous gold mining experience, have significantly higher death rates than the male population of Ontario, adjusted for age and calendar period.

(2) The increased death rate from all causes in both underground mining cohorts is largely the result of a significantly increased death rate for violent causes. The death rate for disease causes is not significantly increased.

(3) Both underground miner cohorts show a significantly increased death rate for malignant neoplasms of the trachea, bronchus and lung.

(4) Uranium miners with prior gold mining experience have a significantly increased risk of dying of cancer of the stomach. No increased death rate for stomach cancer was observed in uranium miners with no previous gold mining experience.

(5) The death rate for cancer of the lymphatic and haematopoietic tissue or for any of the specific causes included in this group was not increased in any of the sub-cohorts.

(6) The death rate for silicosis and chronic interstitial pneumonia was significantly increased in both underground uranium miner cohorts.

(7) No increased death rate for any group of causes was observed in mill workers.

(8) Using the relative risk model, and lagging exposure by five years, the data from the Ontario uranium miners with no prior gold mining experience show an increase in lung cancer risk of 1.3 per cent per WLM. The absolute risk model indicates that the exposure to 1 WLM increases the lung cancer death rate by 5.2×10^{-6} per person-year at risk.

(9) Ontario uranium miners with previous gold mining experience have a risk in addition to the risk resulting from exposure to radon progeny in uranium mines. This is the risk associated with their prior gold mining experience.

(10) Using a relative risk model modified by time since exposure, 1 WLM accumulated in a time window five/nine years preceding the time of observation increases the expected number of lung cancer deaths by 1.6 per cent. One WLM accumulated in the time window 10 to 14 years before the time of observation increases the expected number of lung cancer deaths by 3.4 per cent. Exposure accumulated 15 or more years ago increases the expected number of deaths by 0.3 per cent per WLM. The most effective exposure occurred 10 to 14 years before the time of observation.

(11) The results of the comparison of lifetime risk predicted using Model I and Model II under different conditions of exposure are given. The risk calculated with the use of Model II gives, as a rule, a smaller lifetime risk than that calculated using Model I. This applies to the greatest extent if exposure occurred early in life and over a limited time span only.

(12) The interaction of cigarette smoke and exposure to radon progeny was investigated. The results are compatible with a hypothesis that the effects of inhaled cigarette smoke and radon progeny are multiplicative in a relative risk model.

(13) Uranium miners show a significantly larger proportion of small cell undifferentiated cancers than other hard rock miners. This was found, however, to be largely the result of the younger age of uranium miners. When the fractions of oat cell cancers in uranium and non-uranium miners of similar ages are compared, the difference largely disappeared. The cell type of lung cancer cannot be used to distinguish radiation-induced lung cancers from those due to other causes.

(14) More than 90 per cent of the underground uranium miners survived to the end of the study on December 31, 1981. Conclusions will have to be re-evaluated and refined as more data become available.

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TABLE 1
STANDARDIZED MORTALITY RATIOS IN URANIUM MINERS 1955 - 1981

Cause of Death	Non-gold Uranium Miners				Gold Uranium Miners			
	Observed	Expected	SMR	P-Value	Observed	Expected	SMR	P-Value
All Causes	965	853.61	113	$1x10^{-4}$	689	614.43	112	$2x10^{-3}$
All Disease Causes	594	676.44	88		522	536.62	99	
Infective Disease	5	5.22	96		4	3.60	111	
Silicotuberculosis	0	0.03	0		0	0.05	0	
Respiratory Tuberculosis	1	1.16	86		2	1.02	196	
Other Tuberculosis	1	0.53	192		1	0.33	303	
All Other Infective Diseases	3	3.50	86		1	2.20	45	
Malignant Neoplasms	193	180.21	107		173	139.57	124	$4x10^{-3}$
Digestive Organs	44	53.35	82		51	43.62	117	
Stomach	11	11.60	95		19	9.69	196	$5x10^{-3}$
Intestine, Rectum	20	22.26	90		14	18.33	76	
Other Digestive	13	19.49	67		18	15.60	115	
Respiratory System	83	59.58	139	$2x10^{-3}$	92	48.63	189	$2x10^{-8}$
Nose, Nasal Cavities etc.	0	0.60	0		0	0.41	0	
Larynx	3	2.85	105		0	2.19	0	
Trachea, Bronchus, Lung	80	55.57	144	$1x10^{-3}$	92	45.67	201	$1x10^{-9}$
Other	0	0.56	0		0	0.36	0	
Lymphatic and Haematopoietic Tissue	26	21.61	120		6	13.74	44	
Other Malignant Neoplasms	40	45.67	88		24	33.58	71	
Bone	2	0.99	202		0	0.58	0	
Kidney	7	4.82	145		3	3.60	83	
Bladder	1	3.58	28		0	3.55	0	
Brain	10	10.39	96		6	6.12	98	
Prostate	5	4.75	105		3	5.79	52	
Skin	2	4.31	46		3	2.33	129	
All Other Cancers	13	16.83	77		9	11.61	78	

TABLE 1 (Continued)
STANDARDIZED MORTALITY RATIOS IN URANIUM MINERS 1955 - 1981

Cause of Death	Non-gold Uranium Miners				Gold Uranium Miners			
	Observed	Expected	SMR	P-Value	Observed	Expected	SMR	P-Value
Diseases of Circulatory System	279	349.36	80		242	292.68	83	
Ischaemic Heart Disease	204	270.38	75		179	225.01	80	
Cerebrovascular Disease	37	35.54	104		23	32.10	72	
Other	38	43.44	87		40	35.57	112	
Diseases of Respiratory System	36	34.10	106		39	30.44	128	
Influenza, Pneumonia, etc.	20	25.05	80		23	22.43	103	
Silicosis, Chronic Interstitial Pneumonia	6	1.54	390	5×10^{-3}	9	1.39	647	2×10^{-5}
Other	10	7.51	133		7	6.62	106	
All Other Disease Causes	81	107.55	75		64	70.33	91	
Accidents, Poisoning, Violence	371	177.17	209	$<10^{-11}$	167	77.81	215	$<10^{-11}$
Motor Vehicle Traffic	110	57.49	191	5×10^{-10}	38	22.95	166	2×10^{-3}
Water Transport Accidents	15	7.15	210	7×10^{-3}	7	2.92	240	0.03
Accidental Falls	21	10.26	205	2×10^{-3}	21	6.06	347	2×10^{-6}
Motor Vehicle Non-traffic	2	1.49	134		2	0.64	313	
Accidental Drowning and Submersion	9	6.21	145		3	2.61	115	
Inhalation or Ingestion of Food Causing Obstruction	4	2.95	136		0	1.61	0	
Blow From Falling or Projected Missile	48	4.54	1057	$<10^{-11}$	25	1.93	1295	$<10^{-11}$
Firearms or Explosives	10	1.68	595	1×10^{-5}	6	0.73	822	1×10^{-4}
Other Vehicle Accidents	17	1.42	1197	$<10^{-11}$	5	0.58	862	3×10^{-6}
All Other Accidents	135	83.98	161	2×10^{-7}	60	37.78	159	5×10^{-4}

TABLE 2
STANDARDIZED MORTALITY RATIOS FOR MILL WORKERS
1955–1981

Cause of Death	Observed	Expected	SMR	P-Value
All Causes	46	53.77	86	
All Disease Causes	32	44.31	72	
Infective Disease	0	0.31	0	
Silicotuberculosis	0	0.00		
Respiratory Tuberculosis	0	0.08	0	
Other Tuberculosis	0	0.03	0	
All Other Infective Diseases	0	0.20	0	
Malignant Neoplasms	9	11.58	78	
Digestive Organs	2	3.52	57	
Stomach	0	0.77	0	
Intestine, Rectum	2	1.48	135	
Other Digestive	0	1.27	0	
Respiratory System	4	3.87	103	
Nose, Nasal Cavities etc.	0	0.03	0	
Larynx	0	0.18	0	
Trachea, Bronchus, Lung	4	3.63	110	
Other	0	0.03	0	
Lymphatic and Haematopoietic Tissue	0	1.28	0	
Other malignant Neoplasms	3	2.91	103	
Bone	0	0.06	0	
Kidney	1	0.30	333	
Bladder	0	0.27	0	
Brain	1	0.57	175	
Prostate	0	0.45	0	
Skin	0	0.24	0	
All Other Cancers	1	1.02	98	
Diseases of Circulatory System	18	23.56	76	
Ischaemic Heart Disease	18	17.98	100	
Cerebrovascular Disease	0	2.62	0	
Other	0	2.96	0	
Diseases of Respiratory System	1	2.48	40	
Influenza, Pneumonia, etc.	0	1.82	0	
Silicosis, Chronic Interstitial Pneumonia	1	0.11	909	
Other	0	0.55	0	
All Other Disease Causes	4	6.38	63	
Accidents, Poisoning, Violence	14	9.46	148	
Motor Vehicle Traffic	6	3.08	195	
Water Transport Accidents	0	0.37	0	
Accidental Falls	0	0.59	0	
Motor Vehicle Non-traffic	0	0.08	0	
Accidental Drowning and Submersion	0	0.33	0	
Inhalation or Ingestion of food	1	0.17	588	
Blow From Falling or Projected Missile	0	0.23	0	
Firearms or Explosives	0	0.09	0	
Other Vehicle Accidents	0	0.08	0	
All Other Accidents	7	4.44	158	

TABLE 3
DATA USED TO FIT LAGGED EXPOSURE RESPONSE MODELS

Five year lag period and standard WLM's

	Non-gold Uranium Miners				Gold-Uranium miners			
WLM Interval	Mean WLM	Obs	Exp	P-Y	Mean WLM	Obs	Exp	P-Y
0	0.0	6	2.3	4.8	0.0	5	2.5	1.9
0.1 - 6	3.0	10	10.5	3.6	3.0	15	8.1	1.6
6.1 - 20	11.8	12	16.2	4.7	12.2	21	11.9	1.9
20.1 - 40	29.5	16	10.4	2.9	29.1	14	8.1	1.2
40.1 - 70	53.3	11	6.8	1.7	53.4	11	6.6	0.8
70.1 -140	97.0	12	5.6	1.2	97.8	15	5.4	0.6
140.1+	200.3	13	3.6	0.7	203.4	11	3.0	0.3

Ten year lag period and standard WLM's

	Non-gold Uranium Miners				Gold-Uranium miners			
WLM Interval	Mean WLM	Obs	Exp	P-Y	Mean WLM	Obs	Exp	P-Y
0	0.0	11	7.0	9.3	0.0	15	7.3	3.8
0.1 - 6	3.1	10	9.8	2.5	3.0	12	7.3	1.1
6.1 - 20	11.9	13	15.0	3.3	12.1	21	10.8	1.4
20.1 - 40	29.4	13	9.6	2.0	29.1	12	7.4	0.8
40.1 - 70	53.2	10	6.3	1.2	53.3	12	5.8	0.5
70.1 -140	97.0	13	4.9	0.8	97.2	13	4.4	0.4
140.1+	194.7	10	2.9	0.4	199.5	7	2.4	0.2

Fifteen year lag period and standard WLM's

	Non-gold Uranium Miners				Gold-Uranium miners			
WLM Interval	Mean WLM	Obs	Exp	P-Y	Mean WLM	Obs	Exp	P-Y
0	0.0	27	17.0	13.5	0.0	30	16.3	5.6
0.1 - 6	3.0	11	8.2	1.5	3.1	8	5.9	0.6
6.1 - 20	11.9	10	12.3	2.0	12.1	22	8.7	0.8
20.1 - 40	29.3	12	7.8	1.2	29.0	10	5.9	0.5
40.1 - 70	52.9	7	5.0	0.7	53.3	8	4.4	0.3
70.1 -140	97.0	10	3.5	0.4	96.7	10	2.9	0.2
140.1+	185.6	3	1.6	0.2	192.9	4	1.4	0.1

Notes:

Mean WLM = weighted average using the expected number of deaths as weights

Obs = Observed number of lung cancer deaths

Exp = Expected number of lung cancer deaths based on Provincial rates for males

P-Y = Person-years at risk in ten thousands

TABLE 4
EXPOSURE-RISK FUNCTIONS IN URANIUM MINERS

Attributable Risk Function: (Obs–Exp)/P–Y =A + B x WLM_L

Lag (Years)	Cohort	A x 10^5	B x 10^6	N
5	No Gold	3.4	5.2***	7
	Gold	20.9**	12.9***	7
	All	7.3**	7.8***	7
10	No Gold	2.8	7.4***	7
	Gold	24.6**	16.7***	7
	All	8.4***	10.5***	7
15	No Gold	6.9*	7.4*	7
	Gold	28.4***	26.2***	7
	All	13.0***	13.2***	7

Excess Relative Risk Function (Obs–Exp)/Exp = A + B x WLM_L

Lag (Years)	Cohort	A	B x 100	N
5	No Gold	–0.05	1.3***	7
	Gold	0.7**	0.9*	7
	All	0.3	1.1**	7
10	No Gold	0.01	1.3***	7
	Gold	0.8***	0.7***	7
	All	0.4**	1.0***	7
15	No Gold	0.3	0.7	7
	Gold	0.8***	0.8	7
	All	0.5***	0.7*	7

Notes:

* means $0.01 < p <= 0.05$

** means $0.001 < p <= 0.01$

*** means $p <= 0.001$

N = the number of points used in the regression calculation

Obs = Observed number of lung cancer cases

Exp = Expected number of lung cancer cases

P–Y = Person–years at risk

WLM_L = Exposure to radon progeny lagged by L years.

TABLE 5
DATA USED TO FIT MODEL II

Obs	Exp	P–Y	Age	Mean WLM in each time window: Weighted by expected T_{5-9}	Weighted by expected T_{10-14}	Weighted by expected T_{15+}	Weighted by P–Y T_{5-9}	Weighted by P–Y T_{10-14}	Weighted by P–Y T_{15+}
2	0.395	41279.5	1	0.0	0.0	0.0	0.0	0.0	0.0
0	0.122	3521.5	1	0.0	0.0	8.4	0.0	0.0	8.4
0	0.017	501.0	1	0.0	0.0	50.0	0.0	0.0	50.0
0	0.350	10227.0	1	0.0	9.1	0.0	0.0	9.6	0.0
1	0.069	1850.5	1	0.0	9.9	9.9	0.0	10.2	9.8
0	0.012	335.5	1	0.0	12.0	56.0	0.0	12.0	55.8
0	0.062	1609.0	1	0.0	50.9	0.0	0.0	51.5	0.0
0	0.018	456.0	1	0.0	59.3	12.4	0.0	58.3	12.1
0	0.009	255.0	1	0.0	66.3	74.2	0.0	67.17	74.0
0	0.424	26282.0	1	9.6	0.0	0.0	10.3	0.0	0.0
0	0.002	72.0	1	5.5	0.0	9.8	5.6	0.0	9.9
0	0.000	11.0	1	6.2	0.0	58.5	6.2	0.0	58.4
0	0.147	5183.5	1	10.0	10.2	0.0	10.0	10.9	0.0
0	0.007	195.0	1	7.7	12.8	10.4	7.7	13.0	10.3
0	0.002	64.5	1	8.2	15.3	58.7	8.2	15.3	59.1
0	0.044	1201.5	1	12.8	57.7	0.0	13.0	59.3	0.0
0	0.008	218.0	1	11.4	82.0	12.3	11.3	82.6	12.0
0	0.004	101.0	1	10.3	104.7	74.5	10.3	111.0	74.6
1	0.125	6336.0	1	59.0	0.0	0.0	59.9	0.0	0.0
0	0.053	1765.0	1	71.7	12.4	0.0	73.8	12.9	0.0
0	0.000	8.0	1	53.5	18.3	9.6	52.6	18.6	9.5
0	0.043	1159.0	1	77.8	70.2	0.0	76.8	70.1	0.0
0	0.003	79.5	1	60.9	110.5	9.0	63.2	104.1	8.7
0	0.001	30.0	1	57.1	125.8	54.0	60.0	125.3	53.3
3	0.951	5823.5	2	0.0	0.0	0.0	0.0	0.0	0.0
4	4.136	16981.0	2	0.0	0.0	10.8	0.0	0.0	11.0
2	1.397	5452.5	2	0.0	0.0	63.5	0.0	0.0	64.1
2	1.518	7090.0	2	0.0	10.3	0.0	0.0	10.3	0.0
1	0.790	3409.0	2	0.0	10.0	11.2	0.0	10.0	11.4
0	0.451	1755.5	2	0.0	11.5	76.0	0.0	11.6	74.7
2	0.346	1598.5	2	0.0	52.5	0.0	0.0	52.5	0.0
0	0.233	984.5	2	0.0	61.0	13.6	0.0	60.8	13.9
0	0.233	979.5	2	0.0	64.4	77.1	0.0	64.2	77.8
1	1.366	7206.0	2	10.3	0.0	0.0	10.2	0.0	0.0
0	0.036	159.0	2	4.4	0.0	13.2	4.0	0.0	13.7
0	0.030	108.0	2	2.0	0.0	69.9	1.8	0.0	69.9
1	0.587	2843.0	2	10.4	11.3	0.0	10.3	11.4	0.0
0	0.087	376.0	2	8.6	14.2	15.8	8.5	14.5	16.1
0	0.097	383.5	2	9.0	17.4	64.3	9.1	17.9	65.0
1	0.239	1138.5	2	13.2	59.9	0.0	13.2	60.9	0.0

TABLE 5 (Continued)
DATA USED TO FIT MODEL II

				Mean WLM in each time window					
				Weighted by expected			Weighted by P-Y		
Obs	Exp	P-Y	Age	T_{5-9}	T_{10-14}	T_{15+}	T_{5-9}	T_{10-14}	T_{15+}
0	0.103	449.0	2	13.0	78.1	12.3	13.1	76.8	12.5
1	0.113	442.0	2	12.6	83.1	92.5	12.6	83.0	96.7
1	0.485	2510.0	2	62.7	0.0	0.0	62.8	0.0	0.0
0	0.000	1.0	2	56.8	0.0	30.8	56.8	0.0	30.8
2	0.248	1214.0	2	73.8	12.9	0.0	75.3	12.9	0.0
0	0.003	12.0	2	41.0	13.8	11.2	40.3	13.5	11.9
0	0.001	4.0	2	45.9	19.3	69.5	42.6	18.7	101.6
1	0.220	1025.0	2	80.2	74.8	0.0	80.2	75.9	0.0
1	0.050	221.0	2	63.1	117.7	12.0	62.4	119.2	11.8
1	0.039	154.5	2	44.0	120.4	76.0	44.1	122.4	78.1
1	0.971	1106.5	3	0.0	0.0	0.0	0.0	0.0	0.0
13	15.91	10954.0	3	0.0	0.0	11.0	0.0	0.0	10.8
10	7.323	4845.5	3	0.0	0.0	66.8	0.0	0.0	67.8
1	3.148	2772.0	3	0.0	9.7	0.0	0.0	9.5	0.0
5	1.902	1569.0	3	0.0	10.0	11.6	0.0	9.7	11.7
2	1.731	1230.0	3	0.0	10.9	87.8	0.0	10.9	91.7
2	0.739	656.5	3	0.0	51.6	0.0	0.0	50.8	0.0
2	0.523	445.0	3	0.0	60.5	13.2	0.0	59.6	13.7
5	0.801	605.5	3	0.0	63.4	88.5	0.0	62.9	91.5
1	1.678	1883.5	3	9.8	0.0	0.0	9.4	0.0	0.0
0	0.107	80.0	3	4.8	0.0	15.4	3.9	0.0	15.5
0	0.075	53.5	3	4.0	0.0	68.8	3.2	0.0	64.8
2	0.909	888.0	3	10.0	11.3	0.0	9.6	11.3	0.0
0	0.157	116.5	3	7.6	14.9	16.6	6.9	13.9	16.0
0	0.592	379.5	3	9.2	18.3	65.3	9.1	18.3	69.1
1	0.538	513.5	3	13.7	62.5	0.0	13.7	63.3	0.0
1	0.264	230.5	3	13.3	81.8	12.6	13.3	81.4	12.6
0	0.549	370.0	3	13.6	82.2	117.4	14.1	79.5	123.0
1	0.596	734.0	3	62.7	0.0	0.0	62.4	0.0	0.0
0	0.001	1.0	3	40.7	0.0	0.2	40.7	0.0	0.2
0	0.345	382.0	3	74.5	13.7	0.0	74.0	13.7	0.0
0	0.006	4.0	3	51.3	19.8	12.6	64.2	22.4	15.1
0	0.005	3.0	3	35.7	15.2	89.2	37.0	14.7	66.5
1	0.475	473.0	3	82.5	80.4	0.0	81.7	82.5	0.0
2	0.154	129.5	3	68.4	122.8	13.1	70.4	121.0	13.2
2	0.204	138.5	3	44.9	121.8	76.5	45.5	118.9	78.4

Notes: Obs = Observed lung cancers; Exp = expected lung cancers; P-Y = Person-years at risk; T_{5-9}= Mean WLM in 5-9 year time window; T_{10-14} = Mean WLM in 10-14 year time window; T_{15+} = Mean WLM in 15+ Years time window; Coding for age: 1 = less than 45 years, 2 = 45-54 years, 3 = 55 years or more

TABLE 6
MODEL I AND II RISK FUNCTIONS IN NON-GOLD URANIUM MINERS

Model	Deviance	Degrees Of Freedom
Excess Relative Risk Functions		
$(O-E)/E = -0.12 + 0.015 \times WLM_5$	55.43	74 (Equ 1)
$(O-E)/E = -0.04 + 0.016 \times WLM_{5-9} + 0.034 \times WLM_{10-14} + 0.003 \times WLM_{15+}$	47.90	72 (Equ 2)
$(O-E)/E = -0.04 + 0.091 \times WLM_{5-9} - 0.031 \times AGE \times WLM_{5-9} + 0.021 \times WLM_{10-14} + 0.005 \times AGE \times WLM_{10-14} - 0.003 \times WLM_{15+} + 0.002 \times AGE \times WLM_{15+}$	45.94	69 (Equ 3)
$(O-E)/E = 0.06 + 0.038 \times WLM_{10-14}$	49.76	74 (Equ 4)
$(O-E)/E = 0.06 + 0.049 \times WLM_{10-14} - 0.004 \times AGE \times WLM_{10-14}$	49.72	73 (Equ 5)
Attributable Risk Functions		
$O/P-Y = 3.9 \times 10^{-5} \times A_1 + 3.9 \times 10^{-4} \times A_2 + 1.7 \times 10^{-3} \times A_3$	67.30	73 (Equ 6)
$O/P-Y = 2.4 \times 10^{-5} \times A_1 + 2.7 \times 10^{-4} \times A_2 + 1.5 \times 10-3 \times A_3 + 2.9 \times 10^{-6} \times WLM_5$	60.88	72 (Equ 7)
$O/P-Y = 2.4 \times 10-5 \times A_1 + 2.6 \times 10^{-4} \times A_2 + 1.5 \times 10^{-3} \times A_3 + 1.2 \times 10^{-6} \times WLM_{5-9} + 7.3 \times 10^{-8} \times WLM_{10-4} + 1.5 \times 10^{-6} \times WLM_{15+}$	58.77	70 (Equ 8)

Notes:

WLM_5 = total standard WLM accumulated up to 5 years before risk evaluated
WLM_{5-9} = total standard WLM accumulated 5 to 9 years before risk evaluated
WLM_{10-14} = total standard WLM accumulated 10 to 14 years before risk evaluated
WLM_{15+} = total standard WLM accumulated 15 or more years before risk evaluated
A_1 = 1 if attained age is less than 45 and 0 otherwise
A_2 = 1 if attained age is in the interval 45 to 54 and 0 otherwise
A_3 = 1 if attained age is over 54 and 0 otherwise
$AGE = A_1 + 2 \times A_2 + 3 \times A_3$
O = Observed number of lung cancer deaths
P-Y = Person-years at risk of dying

TABLE 7

RELATIVE RISK OF SMOKING CONTROLLED FOR EXPOSURE TO RADON PROGENY

	No Exposure to Radon Progeny 10 to 14 Years Ago		Some Exposure to Radon Progeny 10 to 14 Years Ago	
Controls	Cases		Cases	
Cigarettes per day in the period 10 years before age of matching cases & controls	Always Fewer than 10 per day	Ever 10 or more per day	Always Fewer than 10 per day	Ever 10 or more per day
Always Fewer than 10 per day	3	17	0	14
Ever 10 or more per day	0	18	1	16
Relative risk of smoking	17/0		14/1	

Note: Matched controls were not available for 3 lung cancer cases

TABLE 8

LUNG CANCER CASES BY ORE, CELL TYPE AND AGE GROUP

Cell type	Non-uranium			Uranium		
	Under 60	60+	Total	Under 60	60+	Total
Squamous	11(18)	34(31)	45(27)	12(17)	9(31)	21(21)
Adenocarcinoma	14(23)	26(24)	40(24)	11(15)	7(24)	18(18)
Small cell	26(43)	31(29)	57(34)	39(54)	11(38)	50(50)
Large cell	8(13)	17(16)	25(15)	10(14)	2(7)	12(12)
Bronchoalveolar	1(2)	0(0)	1(1)	0(0)	0(0)	0(0)
Carcinoid	1(2)	0(0)	1(1)	0(0)	0(0)	0(0)
Total re-examined	61(101)	108(100)	167(102)	72(100)	29(100)	101(101)
Not re-examined	64	121	185	45	267	1
Total	125	229	354	117	55	172

Note: In one non-uranium miner over the age of 60 there were two tumours: one classified as a small cell and the other as a bronchoalveolar. This tumour was classified as a small cell tumour in the above table. For a uranium miner, there were two samples examined: one was classified as a small cell tumour and the other as a adenocarcinoma; this tumour was classified as a small cell tumour in the above table.

FIGURE ONE

RADON PROGENY EXPOSURE AND MEASUREMENTS IN EACH CALENDAR YEAR

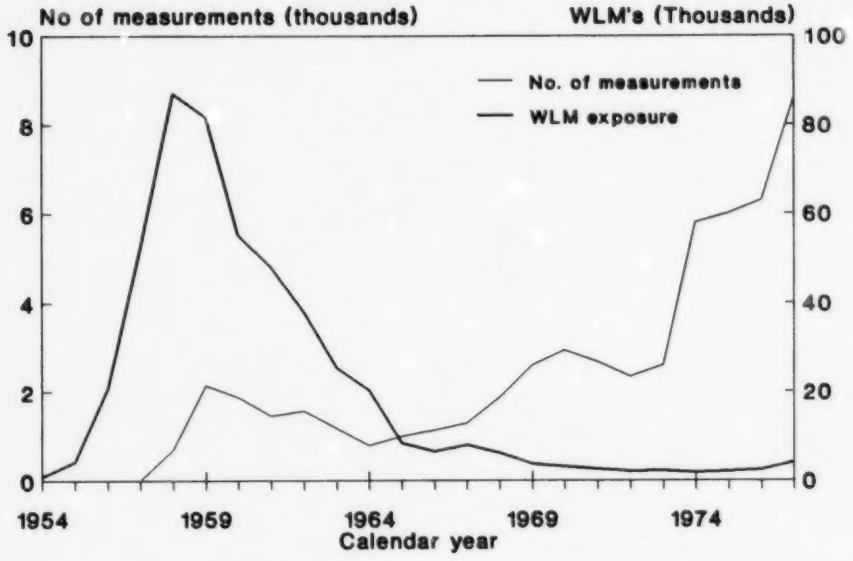


FIGURE TWO

COMPARISON OF STANDARD WLM ESTIMATES AECB & ONTARIO MINERS' STUDY

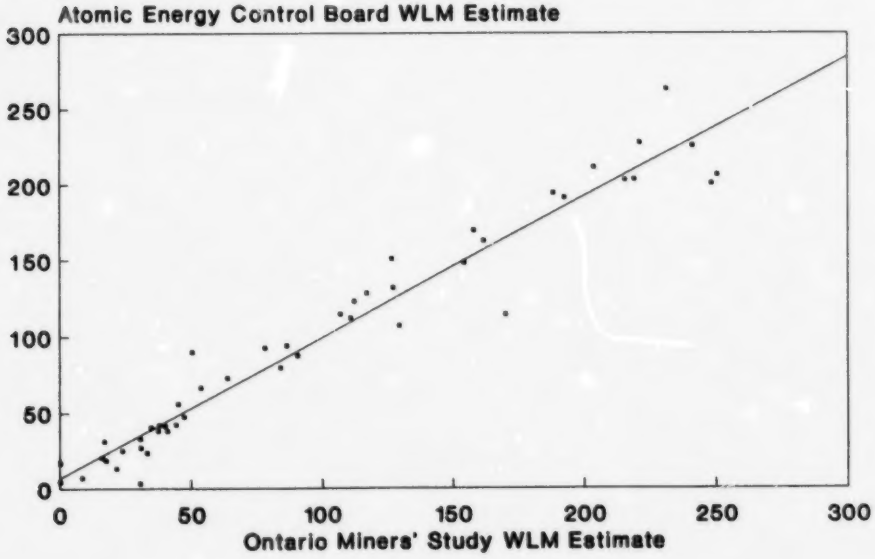


FIGURE THREE

YEAR OF BIRTH FOR URANIUM MINERS

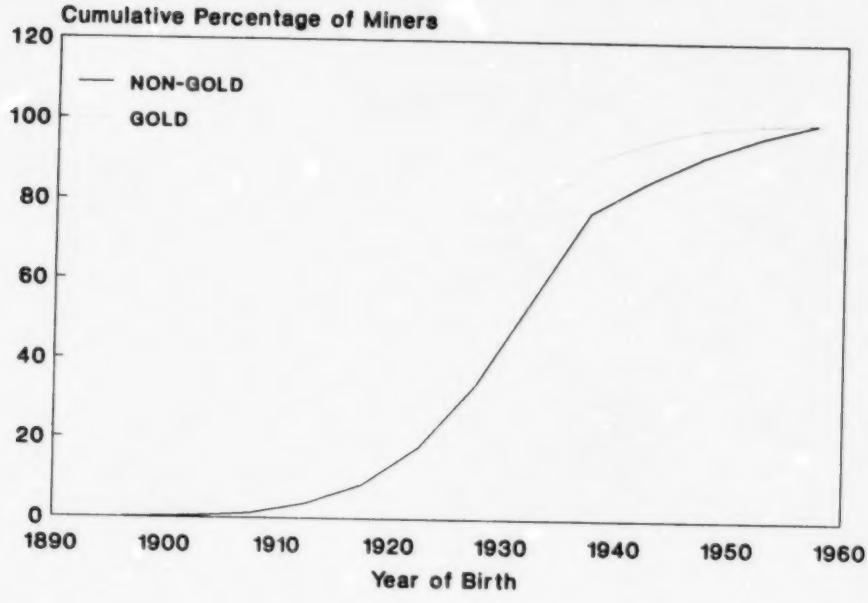
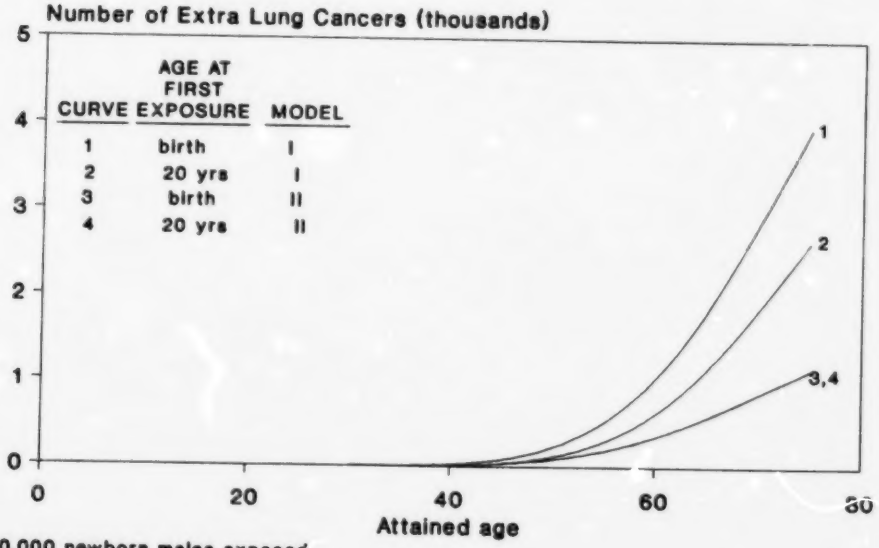


FIGURE FOUR

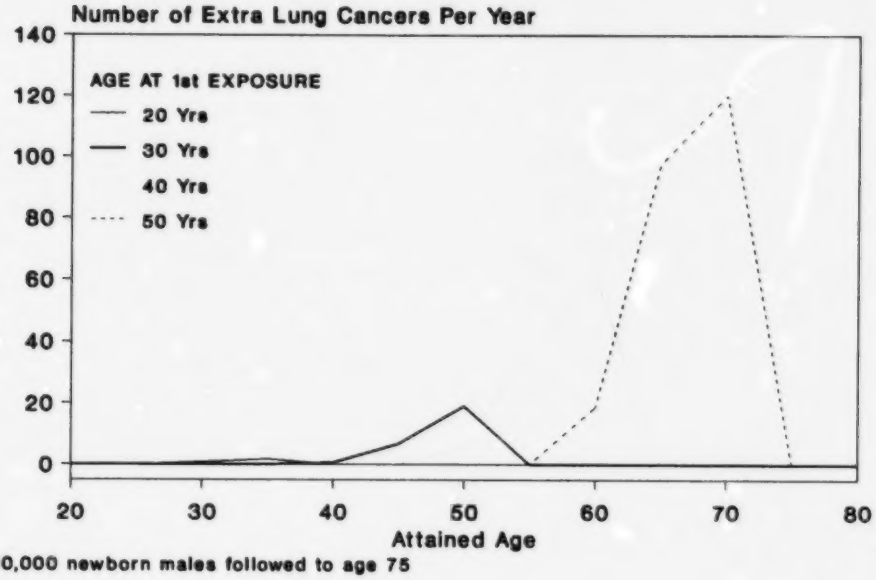
CUMULATIVE NUMBER OF LUNG CANCER CASES BY AGE FIRST EXPOSED & RISK MODEL



100,000 newborn males exposed to 1 WLM/yr from birth or age 20

FIGURE FIVE

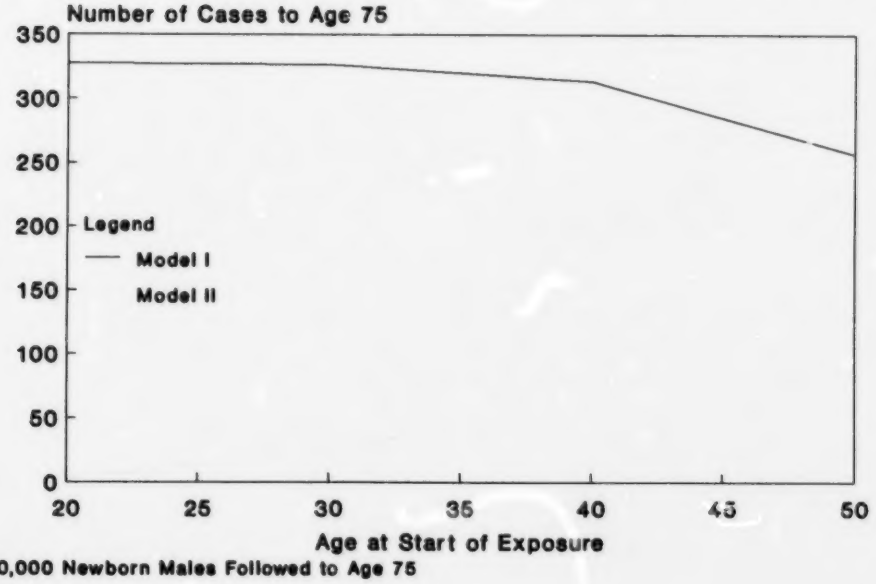
MODEL II RISK ESTIMATES FROM SHORT TERM EXPOSURE AT VARIOUS AGES



100,000 newborn males followed to age 75

FIGURE SIX

PROJECTED LUNG CANCER RISK FROM 5 YEARS' EXPOSURE TO 1 WLM/YR



100,000 Newborn Males Followed to Age 75

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